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Electrofishing for Crappies: Electrical Settings Influence Immobilization Efficiency, Injury, and Mortality

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Abstract.—Continuous direct current (DC) and pulsed DC (PDC) of varying frequency and pulse period are commonly used to immobilize and collect crappies *Pomoxis* spp. in freshwater. However, little information is available about the minimum electrical-setting thresholds required for immobilization or how the settings relate to incidence of injury. We investigated the effect of increasing power densities on the immobilization and injury of black crappies *P. nigromaculatus* (average total length = 154 mm) treated with DC and various PDC settings. Forced swimming toward the electrodes was observed in black crappies exposed to DC, but that was less apparent for PDC. The minimum peak power densities required to immobilize black crappies ranged from 0.10 to 6.5 mW/cm^3 and depended on pulse frequency and period. The incidence of hemorrhaging ranged from 0% to 50% and that of spinal damage from 9% to 45%. However, the severity of injury also depended on pulse frequency and period. No fish suffered mortality at or below the immobilization thresholds, but mortality ranged from 0% to 15% at settings above the thresholds. Mortality was observed with PDC settings of 15 Hz only. Fish that were tetanized following electrical treatment were more prone to injury than those that exhibited narcosis.

Electrofishing is an efficient, commonly used method for collecting fish (Simpson and Reynolds 1977; Steinmetz 1990; Vaux et al. 2000). Fish captured via electrofishing are frequently released after sampling, so it is critical that fish survive and behave normally after release (Schneider 1992). Minimizing electrofishing-induced injury and mortality is especially important when studying populations through mark–recapture methods because death in tagged fish could lead to inflated population estimates or deflated exploitation estimates. Furthermore, reducing fish injury and mortality may be important to Institutional Animal Care and Use Committees (IACUCs) as they evaluate the use of electrofishing for research.

Electrofishing-induced injuries in fish typically include tissue hemorrhage, spinal damage, and mortality (Reynolds 1996). Spinal damage may consist of fracture, misalignment, or compression of the vertebral column. Hemorrhage and bruising due to neural injury and dispersion of melanophores often accompanies spinal injury. These injuries can lead to immediate or delayed mortality (Bardygula-Nonn et al. 1995; Habera et al. 1996), which may occur within a few minutes or a few hours (Reynolds 1996). However, injuries are not always lethal or debilitating, and they often heal, although behavior, health, growth, reproduction, and ultimately survival may be handicapped (Spencer 1967; Hudy 1985; Schill and Elle 2000).

The type of electric current used during electrofishing affects the incidence of injury and mortality. Alternating current (AC) is considered the most injurious, direct current (DC) the least injurious, and pulsed DC (PDC) intermediate to AC and DC (Hauck 1949; Lamarque 1990; Reynolds 1996). In experiments on brook trout *Salvelinus fontinalis*, brown trout *Salmo trutta*, and rainbow trout *Oncorhynchus mykiss*, AC accounted for 11% mortality versus 2% for fish treated with DC (Pratt 1955). Similarly, AC caused 4% mortality in rainbow trout compared with less than 1% for PDC

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and 0% for DC (Taylor et al. 1957). For rainbow trout treated with various PDC settings, incidence of spinal injury ranged 3–62% and increased with pulse frequencies ranging 15–512 Hz (Sharber et al. 1994). In another study, PDC caused a higher incidence of injury in juvenile rainbow trout than did DC, although injuries caused by PDC were less severe (Ainslie et al. 1998). Bluegills *Lepomis macrochirus* suffered up to 12% mortality with AC and up to 2% with DC (Spencer 1967).

Crappies *Pomoxis* spp. are the most harvested species in recreational fisheries in many regions of the USA (Miranda 1999). Populations are often intensively managed to ensure the health of the fishery. In addition to other sampling methods (e.g., trap-netting, gill netting, and trawling), electrofishing has been commonly used to collect crappies (e.g., Maceina and Stimpert 1998; Maceina et al. 1998). However, few studies have addressed injury to warmwater fish caused by electrofishing, and none have addressed crappies. Thus, no guidelines exist as to what electrical settings and voltages result in successful immobilization of crappies without inflicting unacceptable injury and mortality. Also, injury and mortality in crappies that are bycatch of electrofishing surveys targeted at other species with similar habitat requirements (e.g., largemouth bass *Micropterus salmoides*) may be a concern. This lack of information encouraged us to test various electrical settings on black crappies *P. nigromaculatus* so that we could (1) identify immobilization thresholds, (2) estimate the extent of electrofishing-induced injury and mortality, and (3) find methods for minimizing injuries without loss of immobilization efficiency and thereby advance standard electrofishing techniques.

Methods

Electrofishing research was conducted under controlled laboratory conditions at Mississippi State University's National Warmwater Aquaculture Center. Experimentation was performed in a polyethylene plastic tank (2.0 m long, 1.5 m wide, 1.0 m deep). The tank was filled with well water to a depth of 10 cm. Two, 1.6-cm-thick aluminum plate electrodes were positioned in the tank, perpendicular to the longitudinal axis of the tank, and spaced 65 cm apart. Conditions within the tank produced a homogeneous electrical field with a constant voltage gradient. During a treatment, a single fish was placed in the area between the two electrodes, and the electricity switched on when the fish was oriented perpendicular to the electrodes. The reactions of individual fish were visually observed and documented via a video camera positioned over the tank; this allowed review of fish responses to verify observations.

The sampling design for this study was simple random sampling (i.e., fish were haphazardly selected and randomly assigned to a treatment) nested within a sampling-for-modeling experimental design. Sample size was dictated by the amount of data needed to effectively model relationships (e.g., relation between an electrical measurement and immobilization) and was variable. Seven electrical treatments consisting of a combination of pulse frequency and pulse period were considered (Figure 1). These treatments were selected from those commonly used in electrofishing and most readily available in commercial electrofishers. Settings used were no pulse (i.e., DC) and PDC at 15, 60, and 110 Hz. Pulse periods evaluated for PDC were 1, 4, and 6 ms for 15 Hz; 1 ms for 60 Hz; and 1 and 6 ms for 110 Hz. Electricity was supplied to the plates via a Smith Root 15-D POW backpack electrofisher that was modified to allow continuous rather than discrete voltage control. Electrical characteristics between the plates were measured with a Tektronix THS720A oscilloscope.

The black crappies tested averaged 154 mm total length (SD = 15) and 52 g (SD = 17). Fish had been reared indoors for use in culture experiments. All fish had been fed the same diet, had not been previously exposed to electroshock, and had not received any other treatment that could have influenced their condition. Before experimentation, fish were held in concrete raceways for 48 h. A single fish was then captured at random with a dip net from the acclimation raceway and placed in the test tank with the electric current switched off. After allowing 3–10 s for the fish to orient, the current was switched on for 15 s. A total of 24–31 treatment fish and 5–6 control fish (i.e., no electricity applied) were used for each of seven experiments conducted over a 6-week period in October and November 1999. Fish were exposed to power densities that ranged in equal increments from zero to the highest level allowed by the test equipment (one fish per test power density). At each power density we recorded whether the test fish was immobilized within the first 3 s and whether it exhibited narcosis or tetany by the completion of the 15-s period. The 3-s period estimated the time it would likely take a fish to escape the electrical field if the fish was not immobilized, and the 15-s period estimated the maximum amount of time that a fish would be exposed to electricity in an actual field setting. Power density (PD; W/cm^3),

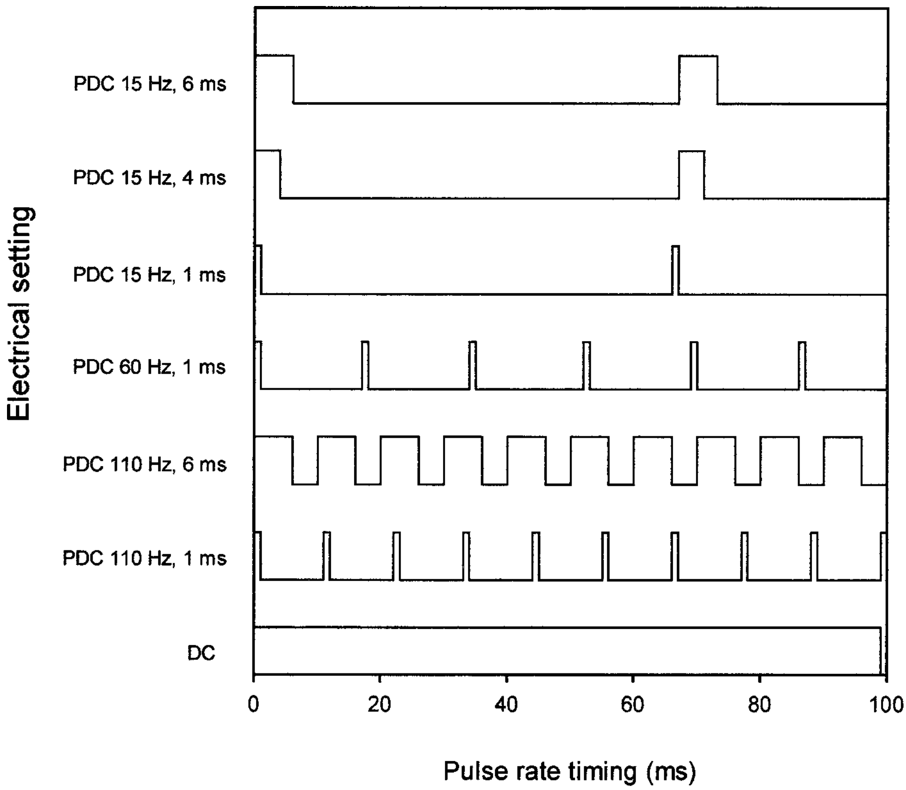


FIGURE 1.—Pulse shape, period, and repetition pattern for seven experimental electrical settings used on black crappies; PDC = pulsed direct current.

a function of conductivity (S/cm) and voltage gradient (V/cm), was computed as follows (Reynolds 1996):

$$\text{PD} = (\text{conductivity})(\text{voltage gradient}^2). \quad (1)$$

The PD was incremented by raising voltage at a nearly constant conductivity that varied only due to small changes in temperature that might have taken place during the 1–2-h treatment period. Fish were treated only once, after which they were transferred to separate aerated 38-L holding tanks and held for 18 h to allow potential hemorrhages to develop and to determine short-term mortality.

Test conditions (temperature and conductivity) were measured with a YSI 30/10 FT conductivity meter. The meter read specific conductivity (C_s) at a specific temperature (T_s) of 25°C. However, electrofishing success depends on conductivity at ambient temperature (T_a). Ambient conductivity (C_a) was estimated from C_s, T_s, and T_a as (Reynolds 1996):

$$C_a = C_s/[1.02^{(T_s - T_a)}] \quad (2)$$

Power density may be computed from peak or root –mean square (RMS) voltage measurements. Peak voltage indicates the maximum applied voltage, whereas RMS is used to facilitate comparisons of electric power among various types of electric currents (Kane and Sternheim 1988). The power density that results upon substitution of peak voltage into equation (1) is referred to as peak power density; alternatively, substitution with RMS voltage results in RMS power density (M. Lee, Centre for Ecology and Hydrology, Windermere, UK, personal communication). Both peak and RMS power densities were estimated; however, preliminary analyses using peak power density yielded models that explained more of the variability in immobilization thresholds, as suggested by comparisons of goodness-of-fit measures. Coincidentally, Kolz and Reynolds (1989) noted that peak power density, instead of RMS power density, correlated better with the behavioral response of goldfish *Carassius auratus*. Therefore, peak power densities were used to develop predictive models, but we also report RMS power densities.

TABLE 1.—Incidence (%) of hemorrhaging, spinal damage, and mortality at power densities above that required for a 95% probability of immobilization in black crappies exposed to direct current and pulsed direct current (PDC) and controls that were not exposed. The values in parentheses represent sample size.

Electrical setting	Hemorrhaging	Spinal damage	Mortality
DC	0 (14)	9 (11)	0 (14)
PDC 110 Hz, 6 ms	43 (14)	20 (10)	0 (14)
PDC 110 Hz, 1 ms	50 (12)	45 (11)	0 (12)
PDC 60 Hz, 1 ms	33 (15)	10 (10)	0 (15)
PDC 15 Hz, 6 ms	14 (14)	20 (10)	7 (13)
PDC 15 Hz, 4 ms	15 (13)	20 (10)	15 (14)
PDC 15 Hz, 1 ms	7 (14)	27 (11)	0 (15)
Controls	0 (16)	0 (20)	0 (16)

Following the 18-h holding period, all fish were euthanized in a solution of 100 mg/L MS-222. Spinal damage was evaluated in a subsample of treatment and control fish selected without known bias (Table 1) after preservation in formalin and subsequent clearing and staining (as per Taylor and Van Dyke 1985). The remaining fish in the sample were necropsied, which included filleting the length of the body just posterior to the pectoral fins, along the rays and spine, to the caudal peduncle. For reference, digital photographs of all filleted fish (lateral view) were taken. Spinal damage and tissue hemorrhage were scored into a binary categorization indicating injury or no injury.

Data analyses.—Immobilization, hemorrhage, spinal injury, and mortality data were analyzed using logistic regression (SAS Institute 1996). The independent variables for these analyses were power density (ratio scale) and electrical setting (nominal scale). Transformations of power density were used when pertinent to improve linearity, homogeneity of variances, and thus, overall fit of the resulting models. The dependent variable was the binary level of behavioral response (i.e., 0 = no immobilization, 1 = immobilization; 0 = no injury, 1 = injury; 0 = alive, 1 = dead). The power density required for a 0.95 probability (PD_{95}) of immobilization was predicted from the logistic regression model. The 0.95 probability was selected because it is associated with high immobilization efficiency (which may translate into increased capture efficiency), but it decreases the likelihood of producing as much injury as with power densities associated with higher probability levels (e.g., PD_{100}). We used Fisher's exact test to compare, across electrical settings, the incidence of hemorrhage, spinal damage, and mortality in fish treated with power densities above PD_{95} (SAS Institute 1996). Fisher's exact test was also applied to test whether incidence of hemorrhage, spinal damage, and mortality differed between the narcosis and tetany endpoints.

Significance for statistical tests involving immobilization was established at $\alpha = 0.05$, and significance of tests involving injury at $\alpha = 0.20$. For immobilization, limiting the probability of a type I error (detecting differences when they do not exist) was important to avoid unwarranted claims regarding differential effectiveness over electrical settings. For injury, the probability of making a type I error was relaxed to err on the side of caution because of the nature of the effect being tested. Of utmost concern was the probability of making a type II error (failing to detect differences in injury when they do exist), which was reduced with a higher alpha level.

Results

A total of 221 black crappies ranging from 119 to 200 mm total length and 21–120 g were tested. Voltages were applied at conductivities of 191–193 μS/cm and temperatures of 20–25°C and ranged from 0 to 1,160 V, translating into voltage gradients of 0–18 V/cm and peak power densities of 0–61 mW/cm^3. Logistic regression models indicated the probability of immobilization was directly related to peak power density ($P < 0.01$), but the effect of power density differed among electrical settings ($P < 0.01$; Table 2). Logistic regression values for the electrical settings indicated the PDC 15-Hz settings (particularly PDC 15 Hz, 1ms) required the greatest peak power densities to immobilize fish (a large negative electrical setting value, β_e, in Table 2 suggests a high peak power density is needed to influence the effect). Values of PD_{95} ranged from 0.10 (PDC 60 Hz, 1ms and PDC 110Hz, 1ms) to 6.5 mW/cm^3 (PDC 15 Hz, 1 ms; Figure 2A). Mid- to high-frequency settings (PDC 60 and 110 Hz) exhibited the lowest PD_{95}; low-frequency settings produced the highest PD_{95}, and DC was intermediate.

No injury or mortality was observed in control fish (Table 1). In treatment fish, all injuries occurred in the caudal peduncle region. Spinal damage usually consisted of the compression of 2–3 caudal vertebrae but without discernible fractures. Hemorrhages occurred at the functional hinge (joint that allows side-to-side movement of the caudal peduncle) of the vertebral column and ranged from 1 to 3 vertebrae in size. Mortality

TABLE 2.—Logistic regression models for predicting the probability (P) of immobilization, hemorrhaging, and spinal damage in black crappies according to electrical setting. Models are of the form logit = $(\beta_0 + \beta_e) + \beta_1 x_i$, where β_0 = intercept, β_e = electrical setting parameter, β_1 = slope, and x_i = power density (mW/cm^3). Different transformations of power density were used for immobilization, hemorrhaging, and spinal damage. For example, the immobilization model for black crappies treated with DC was $(12.9 - 3.97) + 4.26$ [$\log_e$ (power density)]. Logits were back-transformed to probabilities by means of the equation, $P = e^{\text{logit}}/[1 + e^{\text{logit}}]$. For values β_e within the same column that share a letter in common, the differences are not significant (pairwise comparisons were made at $\alpha = 0.05$ for immobilization and $\alpha = 0.20$ for injury).

Parameter	Variable	Immobilization	Hemorrhage	Spinal damage
β_0		12.9	−0.581	−3.20
β_1	$\log_e$ (power density)	4.26		
	Power density^{-1}		−0.131	
	Power density			0.070
β_e	DC	−3.97 zvu	−25.5 z	0.682 z
	PDC 110 Hz, 6 ms	−2.50 zxv	0.565 y	1.49 z
	PDC 110 Hz, 1 ms	−0.202 yxt	0.711 y	1.75 z
	PDC 60 Hz, 1 ms	0 t	0 yw	0 z
	PDC 15 Hz, 6 ms	−5.01 u	−1.20 x	0.864 z
	PDC 15 Hz, 4 ms	−5.02 vu	−1.10 xw	0.839 z
	PDC 15 Hz, 1 ms	−18.0 w	−2.33 zx	−0.347 z

occurred at random intervals over the first 3 h of the 18-h holding period only.

Incidence of hemorrhage above PD_{95} averaged 23% and ranged from 0% (DC) to 50% (PDC 110 Hz, 1 ms) over electrical settings (Table 1; Figure 2B). The logistic regression model indicated the probability of hemorrhage was directly related to power density ($P = 0.03$), but the incidence of hemorrhage above PD_{95} was significantly different among electrical settings ($P < 0.01$; Table 2). Logistic regression values for the electrical settings indicated DC required the greatest peak power densities to induce hemorrhage, and PDC 110 and 60 Hz induced the least. For the PDC settings, hemorrhage appeared to decrease with decreasing frequency and pulse period, but this trend could not be tested statistically because of the limited number of frequencies and pulse period permutations included in this study.

Incidence of spinal damage above PD_{95} averaged 22% and ranged from 9% (DC) to 45% (PDC 110 Hz, 1 ms) over electrical settings (Table 1; Figure 2C). The logistic regression model indicated the probability of spinal damage was directly related to power density ($P = 0.01$). However, the effect of power density did not differ among electrical settings ($P > 0.20$; Table 2).

No mortality was observed above PD_{95} for DC or for PDC at 110 and 60 Hz or at the 15-Hz, 1-ms setting (Table 1). Mortality occurred in the PDC 15-Hz, 6-ms treatment (7%) and PDC 15-Hz, 4-ms treatment (15%) only. A logistic regression model like those developed for hemorrhage and spinal damage could not be fitted because of the low incidence of mortality.

Incidence of hemorrhage for fish narcotized after the 15-s treatment period was 4% ($N = 27$) and differed significantly from the 28% ($N = 80$) exhibited by fish that were tetanized ($P < 0.01$). No mortality ($N = 27$) was observed in fish that exhibited narcosis, but 4% ($N = 80$) of fish that were tetanized died. However, this difference was not statistically significant ($P = 0.57$). Incidence of spinal damage for fish narcotized was 11% ($N = 9$), which did not differ significantly from the 23% ($N = 64$) exhibited by fish that were tetanized ($P = 0.67$).

In addition to the immobilization, injury, and mortality observations summarized above, we made observations about the behavioral reactions of crappies treated with the various electric settings. Because these observations were not conducive to statistical analyses, we provide a descriptive narrative instead. The DC setting caused fish to exhibit electrotaxis (forced swimming) towards the anode (positive electrode) before immobilization (within 3 s); this attraction was conspicuous and occurred immediately upon electrification of the field. However, at high levels of DC (i.e., well above PD_{95}) fish were immobilized instantly, once the field was electrified, without obvious forced swimming towards the anode. Attraction towards the anode was observed in a few fish tested with other settings, but this was not as evident as it was with DC. Fish exposed to low-frequency settings

(PDC 15 Hz) exhibited quivering or strong vibrations after immobilization (such behavior might have occurred before immobilization but could not be observed until fish stopped swimming). Moreover, quivering appeared to be more severe in treatments with low pulse durations (i.e., PDC 15 Hz, 1ms).

Discussion

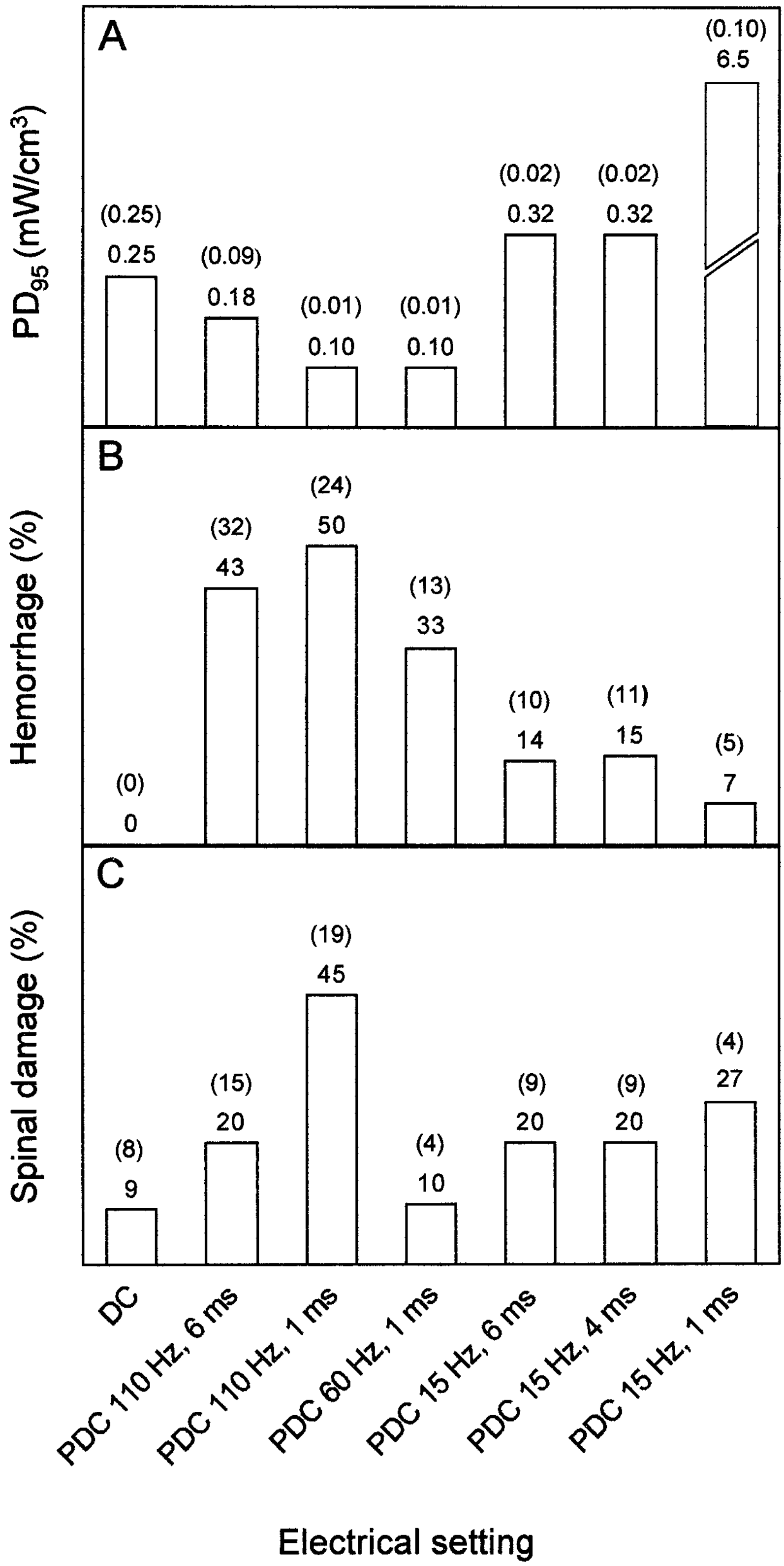
Because fish responses to electrical fields vary with fish size, the PD_{95} values identified are size-specific and projected to be lower for larger black crappies and higher for smaller ones; nevertheless, they provide approximate targets to standardize electrofishing over changing conductivities. A first step towards standardization may be to adjust voltage to homogenize power density over waters with diverse conductivities. To this end, equation (1) serves to adjust voltage output to compensate for a change in conductivity and maintain an approximately constant PD_{95}. A second step towards standardization may be to adjust PD_{95} to compensate for the difference between water and fish conductivities. According to Kolz (1989) PD (and, thus, PD_{95}) varies with water conductivity because the efficiency with which power transfers to the fish depends on the difference between the conductivity of the water and the effective conductivity of the fish; full transfer occurs when conductivities match (Kolz's equation 38 adjusts power transfer for unequal conductivities). Unfortunately, the effective conductivity of a fish changes with electrical setting (Kolz and Reynolds 1989) because fish are not directly wired and have a nervous system that reacts differently to diverse electrical stimuli. In addition, effective conductivity is likely to change with fish species, life stage, and other biological characteristics that affect chemical makeup (thus, electrical conductance). Another limitation to standardizing power transferred to fish is the inability to create homogeneous electrical fields under field conditions (Reynolds 1996). Despite these limitations, efforts to standardize electrofishing to maintain relatively constant power have reduced intersite variability in catch rates (Burkhardt and Gutreuter 1995).

The low-frequency electrical settings required higher PD_{95} to immobilize fish than DC or mid- to high-frequency settings. Vibert (1967) speculated that differences in immobilization between low- and high-frequency electrical settings may be attributed to longer off-times associated with low-frequency settings. These pulse frequencies allow muscles more time to relax before stimulation with the next pulse of electricity; thus, more time or higher peak power density may be required to immobilize fish. Conversely, DC and mid- to high-frequency settings stimulate fish muscles constantly or nearly so, limiting relaxation time and potentially leading to quicker cramping and immobilization at lower peak power densities. A similar scenario may have led to our observations of increased PD_{95} for low-frequency treated fish in this study.

Traditionally, radiography has been used to evaluate spinal damage. However, we used clearing and staining to evaluate spinal injuries in this study, which we believe provided more accurate assessment of spinal damage because fish skeletons could be observed from many different angles, as opposed to only a single perspective for radiography. Furthermore, clearing and staining allowed us to save the actual test specimens for further scrutiny of potential spinal injuries. The drawbacks of clearing and staining are that it is more time-consuming than radiography and nearly as costly.

Incidence of hemorrhage and spinal damage appeared to be linked to pulse frequency, higher frequencies leading to more injuries and lower frequencies or no pulsation to fewer injuries. The two PDC 110 Hz settings produced the most hemorrhages and spinal injuries. Similarly, Sharber et al. (1994) found that incidence of spinal injury increased with pulse frequency in rainbow trout. They hypothesized that more fish injuries occurred at high pulse frequencies because injuries were caused by myoclonic jerks associated with shock-induced seizures, and such seizures developed more rapidly at higher than at lower frequencies. These same mechanisms could be contributing to the high incidence of spinal injury and hemorrhage observed in black crappies treated with the PDC 110-Hz settings.

Absence of a highly developed muscle mass may make crappies susceptible to hemorrhage and spinal damage. Both crappie species (black crappies and white crappies *P. annularis*) have evolved large dorsal and ventral fins and a laterally compressed body to facilitate maneuverability in their favored habitats, which include submerged structures and steep slopes (Pflieger 1997). This adaptation has led to a reduced muscle mass around the spinal column (Helfman et al. 1997), a deficiency that may contribute to vulnerability to hemorrhage and spinal damage. That is, poorly developed lateral muscles offer little protection or cushion from the effects of anodic curvature, and


A
PD95 (mW/cm3)
(0.25)
0.25
(0.09)
0.18
(0.01)
0.10
(0.01)
0.10
(0.02)
0.32
(0.02)
0.32
(0.10)
6.5
B
Hemorrhage (%)
(0)
0
(32)
43
(24)
50
(13)
33
(10)
14
(11)
15
(5)
7
C
Spinal damage (%)
(8)
9
(15)
20
(19)
45
(4)
10
(9)
20
(9)
20
(4)
27
DC
PDC 110 Hz, 6 ms
PDC 110 Hz, 1 ms
PDC 60 Hz, 1 ms
PDC 15 Hz, 6 ms
PDC 15 Hz, 4 ms
PDC 15 Hz, 1 ms
Electrical setting

severe contortions that result from this curvature may lead to injuries (Lamarque 1990). Black crappies were observed to contort at the functional hinge in the caudal peduncle, where hemorrhage and spinal damage were most prevalent.

Traditionally, electrofishing has been considered most effective when conducted with settings that have maximum tetanizing effects (Lamarque 1990). Our immobilization and injury observations cause us to question this approach. First, although immobilization was more instantaneous when applying electrical power at levels that tetanized fish, the benefits of electrotaxis recorded with DC were lost when fish were tetanized. Second, tetanized fish exhibited more injury, possibly because of severe muscle contractions that can produce tissue and bone damage (Lamarque 1990; Reynolds 1996). Narcosis and tetany endpoints depend on the nature and intensity of the electrical field, managed by manipulating power density through reductions or increases in voltage or amperage (Reynolds 1996). Because injury levels were reduced in fish that were narcotized but not tetanized, operating equipment to produce power densities that induce narcosis rather than tetany can reduce injury. During electrofishing collections in the field, control of electrical output to induce narcosis rather than tetany can be achieved by observing behavior of fish within the electrical field. However, this observational approach would not address the standardization issues pursued by Burkhardt and Gutreuter (1995).

Mortality of black crappies treated with PDC at 15 Hz may be attributed to various factors other than the injuries studied. In a study of rainbow trout, Taylor et al. (1957) concluded that mortality often appeared to result from factors that were not visible either grossly or microscopically. For example, the persistence of tetany after the interruption of current may prevent resumption of respiration, leading to suffocation and eventually death (Lamarque 1990). In addition, researchers have found that electrical current can alter blood constituents, and they have suggested that stress associated with these changes may reduce survival (Barton and Grosh 1996; Barton and Dwyer 1997). We observed in our study that fish treated with PDC at 15 Hz, unlike other electrical settings, vibrated or quivered vigorously. This vibration was consistent with the symptoms (twitches, jerks, and convulsions) of epileptic seizure described by Sharber and Black (1999), who stated that seizures could be induced in many vertebrates (including fish) by passage of electrical current through the brain. Epileptic seizures have been suggested as cause for gross physical injuries such as spinal damage (Sharber et al. 1994), and it follows that seizures may also result in less detectable injuries (i.e., organ, tissue, and cell damage) that may eventually lead to death. Such a scenario may have contributed to death of fish in our experiment. However, because little information exists regarding the effect of seizure on mortality, additional research is needed to identify the precise cause of death of black crappies exposed to low-frequency electrical pulses. In the meantime, it may be best to avoid the use of low-frequency electrofishing to minimize mortality of shocked black crappies. Also, it may be appropriate to exercise the same caution when electrofishing for white crappies. Black crappies and white crappies frequently occupy the same habitats and, in most respects, have similar biology (Pflieger 1997).

In conclusion, our research showed that electrofishing with enough power to immobilize black crappies resulted in injuries to the fish. High-frequency settings produced the greatest levels of injury, and low frequencies can produce the greatest levels of mortality; DC produced the least injury and mortality. Additionally, black crappies exposed to DC often exhibited forced swimming towards the electrodes, a feature that may allow more efficient extraction of fish from cover or deep water. However, with the DC setting the current was on continuously, necessitating more power than with a PDC setting (greater RMS PD_{95}; Figure 2A), which may decrease the utility of DC electrofishing in low or high conductivity waters (Reynolds 1996). The next best alternative to DC, when low power output is an issue, may be PDC at 60 Hz. This setting requires less power because time-on is reduced compared with other PDC settings with higher or lower frequencies, and that may reduce injury and mortality. The PD_{95} values

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FIGURE 2.—**(A)** Peak power density required to achieve a 95% probability of immobilizing black crappies (PD_{95}), **(B)** hemorrhaging above PD_{95}, and **(C)** spinal damage above PD_{95}. In panel A, the values in parentheses represent root mean squares of PD_{95}; in panels B and C, the values in parentheses represent predicted injuries at PD_{95} (derived from equations in Table 2).

identified provide approximate targets for electrifying black crappies; managing voltage output levels to induce narcosis and avoid tetany provides a suitable alternative to measuring power densities in water and power transferred to fish.

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